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13. ABSTRACT

Shock tubes and high explosives were used to produce blast waves of various pressure-time patterns in order to study their biological effects. Data obtained from these experiments showed that, against a reflecting surface, the LD_{50} reflected pressure for any given species remained fairly constant at the "longer" durations and then rose sharply at the "shorter" times. For dogs and goats, "long" durations were beyond 20 msec and for mice, rats, guinea pigs, and rabbits, beyond 1 to 3 msec. At the "shorter" durations, response depended to a great extent on the impulse, and on peak pressure for the "longer" pulses. Higher reflected pressures can be withstood if animals are located beyond a certain distance from the reflecting surface where they receive the incident and reflected pressures in two steps, separated by a given time-interval. In freestream exposures to air blast, orientation was significant. Animals suspended vertically or prone-side-on showed a lower tolerance to blast waves of a given intensity or at a given range than those end-on because the dynamic pressure appeared to add to their side-on pressure dose. Except for eardrum rupture and sinus hemorrhage, animals exhibited a remarkable tolerance to "slow"-rising blast pressures without the presence of shock fronts.

The lungs are considered the critical target organs in blast effects studies. The release of air bubbles from disrupted alveoli of the lungs into the vascular system probably accounted for the rapid deaths. The degree of lung hemorrhage

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FOREWORD

This report encompasses a paper given at the New York Academy of Sciences' Conference on Prevention of and Protection Against Accidental Explosions of Munitions, Fuels, and Other Hazardous Mixtures during the session entitled Personnel Sensitivity on October 11, 1966. Much of the data has been published before and is referenced accordingly. A considerable portion of the information is new; namely, that dealing with the LD_{50} for monkeys, swine, and sheep for "short"-duration blast waves; the threshold lung injury for sheep at 5- and near 200-msec durations; and the effects of orientation on the tolerance of sheep to blast waves from high explosives. Also new are the refined estimates for personnel tolerance to "short"-duration blast waves including the significance of establishing the pressure dose with respect to one's orientation to the blast source.

The information has a direct bearing on protection of personnel against explosive events and determination of safe dist⁻. ₋es for personnel from explosive materials. It is also usable for weapons effects analysts as well as for those interested in environmental medicine, either military or industrial.

The results reported herein are a part of those gathered in a continuing investigative effort aimed at predicting the response of personnel to air blasts of various waveforms, understanding the nature of injuries—their prognosis and treatment—and formulating protective principles.

ABSTRACT

Shock tubes and high explosives were used to produce blast waves of various pressure-time patterns in order to study their biological effects. Data obtained from these experiments showed that, against a reflecting surface, the LD50 reflected pressure for any given species remained fairly constant at the "longer" durations and then rose sharply at the "shorter" times. For dogs and goats, "long" durations were beyond 20 msec and for mice, rats, guinea pigs, and rabbits, beyond 1 to 3 msec. At the "shorter" durations, response depended to a great extent on the impulse, and on peak pressure for the "longer" pulses. Higher reflected pressures can be withstood if animals are located beyond a certain distance from the reflecting surface where they receive the incident and reflected pressures in two steps, separated by a given time-interval. In freestream exposures to air blast, orientation was significant. Animals suspended vertically or prone-side-on showed a lower tolerance to blast waves of a given intensity or at a given range than those end-on because the dynamic pressure appeared to add to their side-on pressure dose. Except for eardrum rupture and sinus hemorrhage, animals exhibited a remarkable tolerance to "slow"-rising blast pressures without the presence of shock fronts.

The lungs are considered the critical target organs in blast effects studies. The release of air bubbles from disrupted alveoli of the lungs into the vascular system probably accounted for the rapid deaths. The degree of lung hemorrhage was related to both the blast dose and the increase in lung weight over control values. For larger animals, the threshold for petechial hemorrhage was near 10 to 15 psi at "long" durations and 30 to 35 psi for pulses of 5 msec. At LD50 values lung weights were two to four times normal.

Ear injury was not systematically studied; however, data gleaned from lethality and lung-injury experiments indicated that: eardrum response to blast pressures is subject to wide variation; a duration effect was observed in sheep, with 38-per cent rupture recorded at 21.4 psi for durations near 100 msec versus no eardrum rupture at 32.4 psi when the durations were about 5 msec; and the severity of ear damage increased with the intensity of the blast.

From the presented data, tentative estimations of man's response to "fast"-rising pressures of 3-msec duration were compiled. Pressures for threshold and severe lung-hemorrhage levels were 30 to 40 and above 80 psi, respectively. The threshold for lethality was 100 to 120 psi with an LD50 range of 130 to 180 psi. Time-honored estimates for human eardrum rupture values of 5 and 15 psi, respectively, for threshold and 50-per cent could not be revised at this time.

The estimates were given in terms of maximal effective pressures, which may be received from the incident, incident plus dynamic, or reflected pressure, dependent on orientation. For an individual against a reflecting surface that is normal to the incident shock, or prone with the charge detonated overhead, the maximal effective dose is the reflected pressure. If, however, the man is standing a few feet from this same reflecting surface or directly below the charge, he is subjected to pressures

that rise in two steps; whereas, in the former situation, the maximal effective pressure would probably be the incident plus the dynamic pressures in the first step and, in the latter, only the side-on incident pressure in the initial step. The exact distance from a reflecting surface where the effective pressure changes from the reflected to incident, or incident plus dynamic, cannot be stated for man at this time. For personnel standing or prone-side-on to the charge when it is detonated at or near the surface, the side-on incident plus dynamic pressures become the effective pressure; however, with orientations end-on in this situation, only the side-on incident pressure appears to be the maximal effective pressure.

ACKNOWLEDGMENTS

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THE RELATIONSHIP BETWEEN SELECTED BLAST-WAVE PARAMETERS AND THE RESPONSE OF MAMMALS EXPOSED TO AIR BLAST

Donald R. Richmond, Edward G. Damon, E. Royce Fletcher,
I. Gerald Bowen, and Clayton S. White

INTRODUCTION

Even though high explosives were used for hundreds of years, surprisingly little was learned about the biological effects of air blast—least of all, the physical parameters of the blast wave responsible for death and injury. This was probably because the fragments from the explosive container itself were the overriding personnel hazard, particularly in wartime. Toward the end of World War II, however, high-explosive bombs were of sufficient size wherein the blast overpressure was the mechanism for buildings, and destruction from fragments the less important consideration for the larger explosive charges.

With the advent of nuclear explosives, there was a renewed interest in the sensitivity of personnel to air blast. Investigations conducted in Germany, the results of which were not known until the end of the second World War, clearly showed that as the weight of the explosive charge was increased from 50 to 2000 kg with corresponding increases in duration from 1.6 to 11.8 msec, the lethal pressures for dogs dropped by a factor of about three—216 to 75 psi.[1] Since nuclear explosives were equivalent in yield to tremendous quantities of high explosives, they would produce blast waves of very "long" duration which might prove to be extremely hazardous to personnel.

The purposes of this paper are: (1) to summarize results from this laboratory on mammalian tolerance to air blasts—specifically, the relationship between lethality, lung injury, and, to some extent, eardrum rupture in experimental animals and the parameters of the blast wave; and (2) to present estimates of blast levels that would be safe, cause injury, or be lethal to man. As a matter of fact, these should be known before one can economically plan protective measures for man against explosions, be they accidental or otherwise. Attempts will be made to emphasize the effects of "short"-duration blast, arbitrarily defined as those less than 20 msec for large species. It must be remembered, however, that many high-explosive accidents have occurred, and will recur, that have yields greater than those of the smaller nuclear devices, thereby making the included data for "long" durations pertinent.

METHODS

In dealing with air-blast effects, it is important to measure and understand as much as possible of the phenomena involved in order to correlate one or more of the physical parameters with the resultant level of biological response; that is, to establish a dose-response relationship. One must therefore measure the pressure-time curve of the air blast precisely and as close to the animal targets as feasible. For this, piezoelectric transducers having a high-frequency response are used. Usually,

the output of these transducers is amplified and displayed on a cathode-ray oscilloscope. Air blasts have been routinely generated in this laboratory by compressed-air-operated shock tubes and by high explosives fired in the open.[2] The average ambient pressure at this station is 12.0 psia, and, unless otherwise stated, the pressure curves and results apply to that barometric pressure.

Figure 1 presents the pressure-time histories from 64-lb TNT charges. Figure 1A shows the pressure waveforms at the surface and side-on at 2-1/2 and 12 in. above the surface from a charge detonated overhead at an 18-ft burst height. The diagram illustrates the incident shock front traveling outward in a spherical manner. Upon striking the surface, the magnitude of the pressure is magnified two or more times because of reflection. Directly beneath the charge, the flow associated with the incident shock is reversed by the reflected shock which travels in the opposite direction. Gauge "a," at the surface, measures the incident and reflected pressures as a single rise to 146 psi. Gauges "b" and "c," at 2-1/2- and 12-in. heights, record them as two distinct shock fronts separated by times on the order of 0.25 and 1.2 msec, respectively. It can be seen that the reflected pressure decayed markedly over the first one foot of travel and is only one-third what it was on the surface.

Figure 1B gives records taken by gauges at a 20-ft ground range from a 64-lb charge detonated at a 12-ft height-of-burst. At that range and near the surface, the reflected shock has overtaken and merged with the incident shock to form the mach stem; at this point, the flow becomes parallel with the surface. Gauge "d," mounted above the surface face-on to the flow, records the side-on plus dynamic pressure, and gauge "e," mounted side-on in the surface at the same range, registers the side-on pressure. The side-on plus the dynamic pressure is about twice the side-on pressure at that level. The difference between the face-on and side-on pressures is the dynamic pressure. It is equal to the air density times the square of the particle velocity divided by two.

Figure 1B (record e) shows a blast wave as it is usually portrayed measured side-on. It is characterized by a near-instantaneous rise to a peak in the shock front, followed by an almost exponential decay to below ambient. The peak pressure is generally expressed in units of pounds per square inch (psi), atmospheres (atm), or kilograms of force per square centimeter (Kgf/cm^2). The time the pressure remains above normal ambient is termed the duration of the blast wave, which, in this case, is about 3.7 msec. The positive impulse is the integral of $P_d t$ — commonly stated as psi·msec, atm·msec, or msec·Kgf/cm^2. As the wave travels away from the source, it decreases in magnitude and grows in duration.

The reader may recognize the complexity of establishing the air-blast dose by imagining prone and standing personnel in the vicinity of the gauges in Figures 1A and B.

A shock tube is simply a long duct closed at one or both ends. It is divided into a high-pressure side (compression chamber) and a low-pressure side (expansion chamber) by a rupturable diaphragm. At diaphragm rupture, the release of the high-pressure gas generates a shock front that travels down the expansion chamber. Except at long distances downstream (approximately 16 times the length of the high-pressure chamber), the shock wave in the tube is typically flat-topped. This is in contrast to the peaked waves from high explosives.

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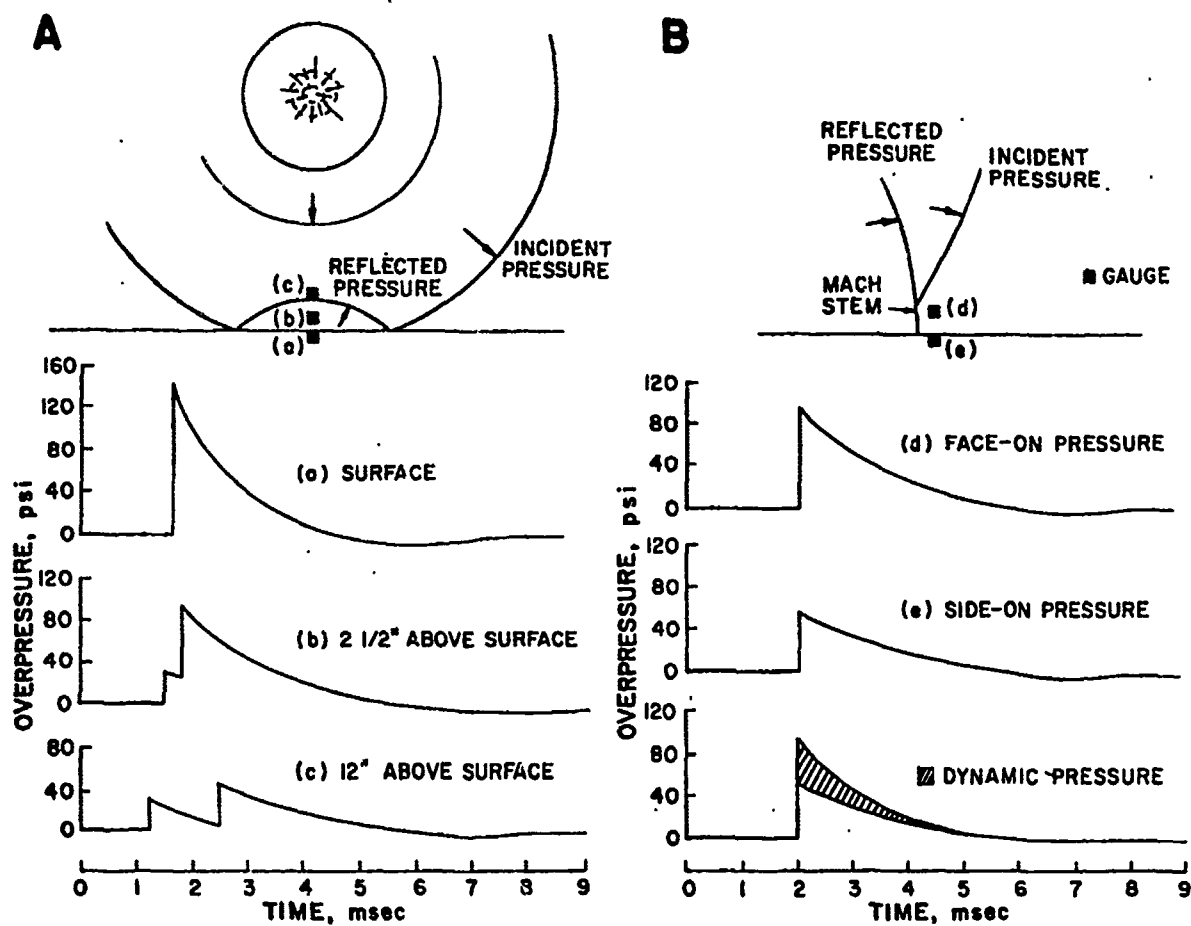
Figure 1. Pressure-Time Histories from 64-Lb TNT Charges. Figure
A Is Pressure-Time Recordings from Piezoelectric Gauges
Mounted (a) Flush with the Ground Surface and (b) and (c)
Side-On at 2-1/2 and 12 In., Respectively, above the Surface.
Height-of-Burst Was 18 Ft. Figure B Is Pressure-Time
Recordings from Piezoelectric Gauges Mounted (d) Face-On
and (e) Side-On at 20-Ft Ground Range and 12-Ft Burst Height.
All Measurements Were Made at an Ambient Pressure of 12
Psia.

Figures 2A and B illustrate the pressure-time histories in a closed shock tube used to generate reflected shocks and in an open-ended one for freestream conditions. It should be pointed out that the same physical laws that govern the behavior of shock waves in the air from high explosives also apply to those in shock tubes — except it must be borne in mind that, in the shock tube, the wave is traveling in only one direction. By modifying the configuration of the shock tube, the air-blast pattern can be tailored to a great extent in regard to magnitude, duration, and nature of the leading edge of the pulse. One big advantage of shock tubes in simulating blasts is that "long"-duration waves are readily obtained that would otherwise require large amounts of high explosives.

BIOLOGICAL TOLERANCE TO "SHARP"-RISING
PRESSURES OF VARIOUS DURATIONS

The geometries of exposure in these studies were those in which animals were placed against a reflecting surface either left-side-on against the endplate that closed the end of the expansion chamber of the shock tube (Figure 2A) or in the prone position on a concrete pad with the charges detonated overhead (Figure 1A). In both instances, the maximal "load" received by the subjects was the reflected pressure. For the most part, the "long"-duration pulses were from the shock tubes and the "short" ones from high explosives.

Dose-response data in the form of probit mortality curves relating the per-cent mortality at 24 hours to the log reflected pressure for "long" (180 to 400 msec)[3-5] and "short" (2.1 to 4.6 msec)[3,6,7] durations appear in Figures 3 and 4, respectively. Tables 1 and 2 give the corresponding LD_{50} values, probit regression equation constants, and related animal information. Statistical analysis showed that the slopes of the curves did not vary significantly from one another, and so they were adjusted to a common slope in both cases.

That the mortality curves are essentially parallel suggests that all species are dying from similar mechanisms; a prominent one of which is the consequence of air emboli entering the vascular system from the damaged lungs and traveling to the heart and brain. The steep slopes of the curves indicate a relatively small range in pressure dose from the LD_1 to the LD_{99} levels. It is a sort of "all"- or "none"-type response. In terms of ground range from a small explosion, this establishes a relatively short zone between the distance at which all the animals are killed and the range beyond which they all survive. As an example, for sheep prone-side-on, it was roughly between 17- and 21-ft ground ranges from a 64-lb charge at a 6-ft burst height.

The LD_{50} curves in Figures 3 and 4 fall into two groups. Into one group fall small rodents (mice, hamsters, rats, guinea pigs, and rabbits) and into the other, the larger animals (dogs, goats, sheep, cattle, and swine). Cats and monkeys also fall into the larger-animal grouping by virtue of their tolerance.

In Figure 5, the above LD_{50} values, as well as those reported elsewhere,[8-10] for "sharp"-rising reflected pressures are plotted as a function of duration. It can be seen that, for a given species, the median lethal
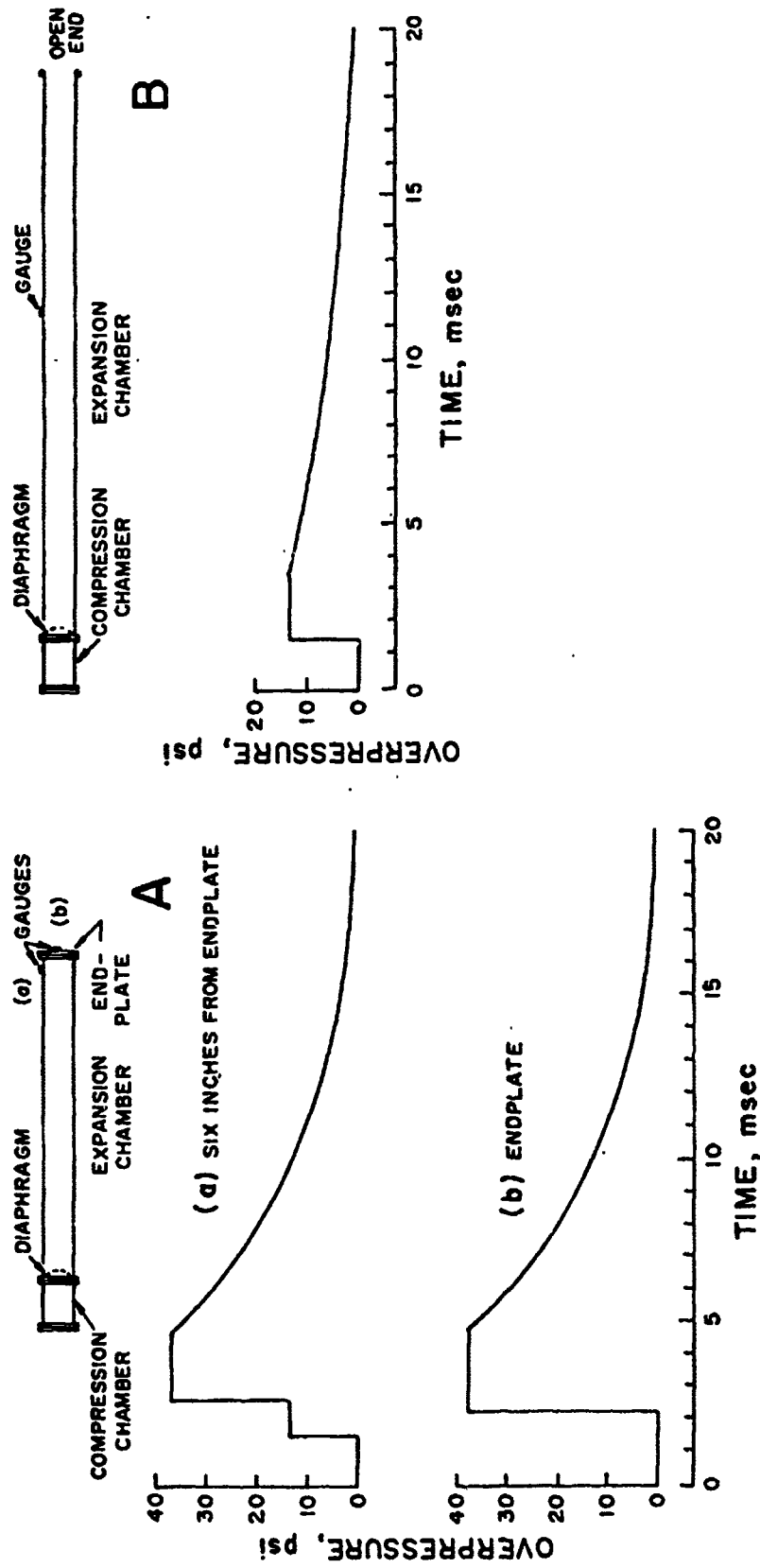
Figure 2. Pressure-Time Histories from 12-In. Diameter Shock Tube. Figure A Is Recordings from a Shock Tube Fired Closed-End (a) with Gauge Mounted Side-On in the Wall of the Tube 6 In. Upstream from the Endplate and (b) Gauge Mounted Flush with the Inner Surface of the Endplate. Figure B Is a Recording from a Shock Tube Fired Open-Ended with the Gauge Mounted Side-On 17 Ft from the Diaphragm. All Measurements Were Made at an Ambient Pressure of 12 Psia.
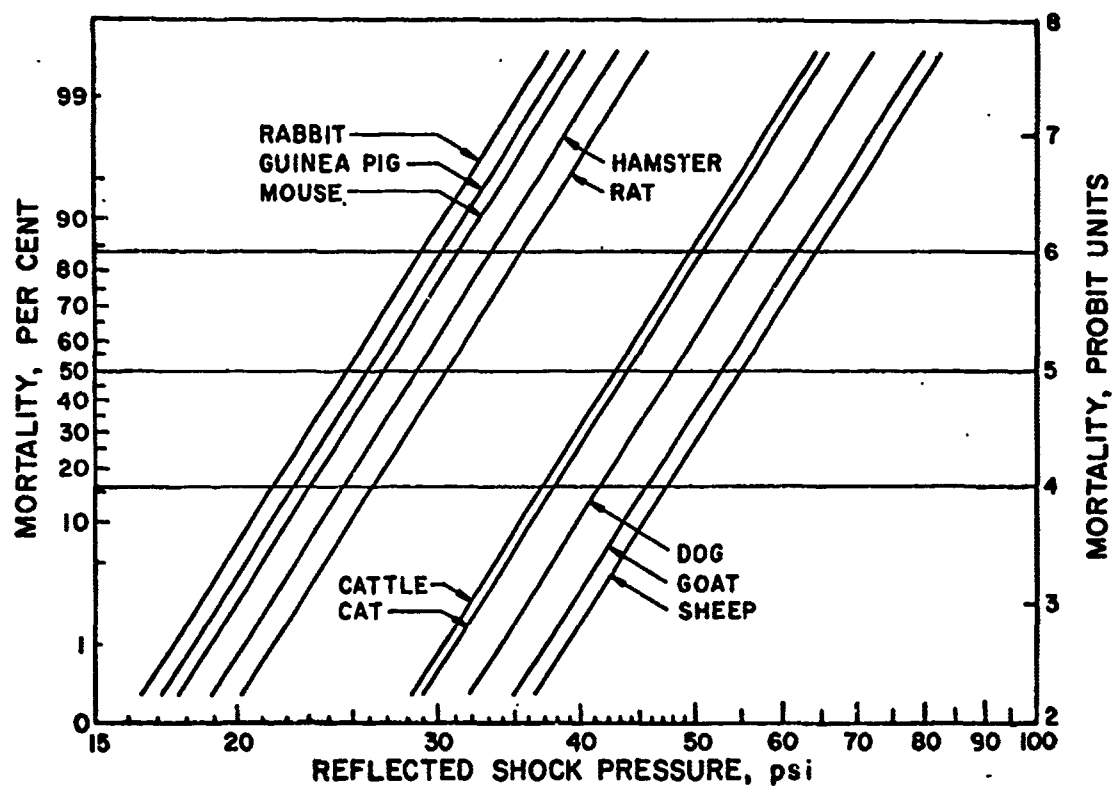
Figure 3. Mortality Curves for Animals Exposed to "Long"-Duration
Reflected Pressures While Mounted Side-On Against the
Endplate of a Shock Tube. Probit Regression Equation:
$y = a + b \log x$; Where y Is the Per-Cent Mortality in Probit
Units, a and b the Intercept and Slope Constants, and x the
Pressure. Data Taken from References 3 to 5; All
Measurements Were Made at Ambient Pressure of 12 Psia.
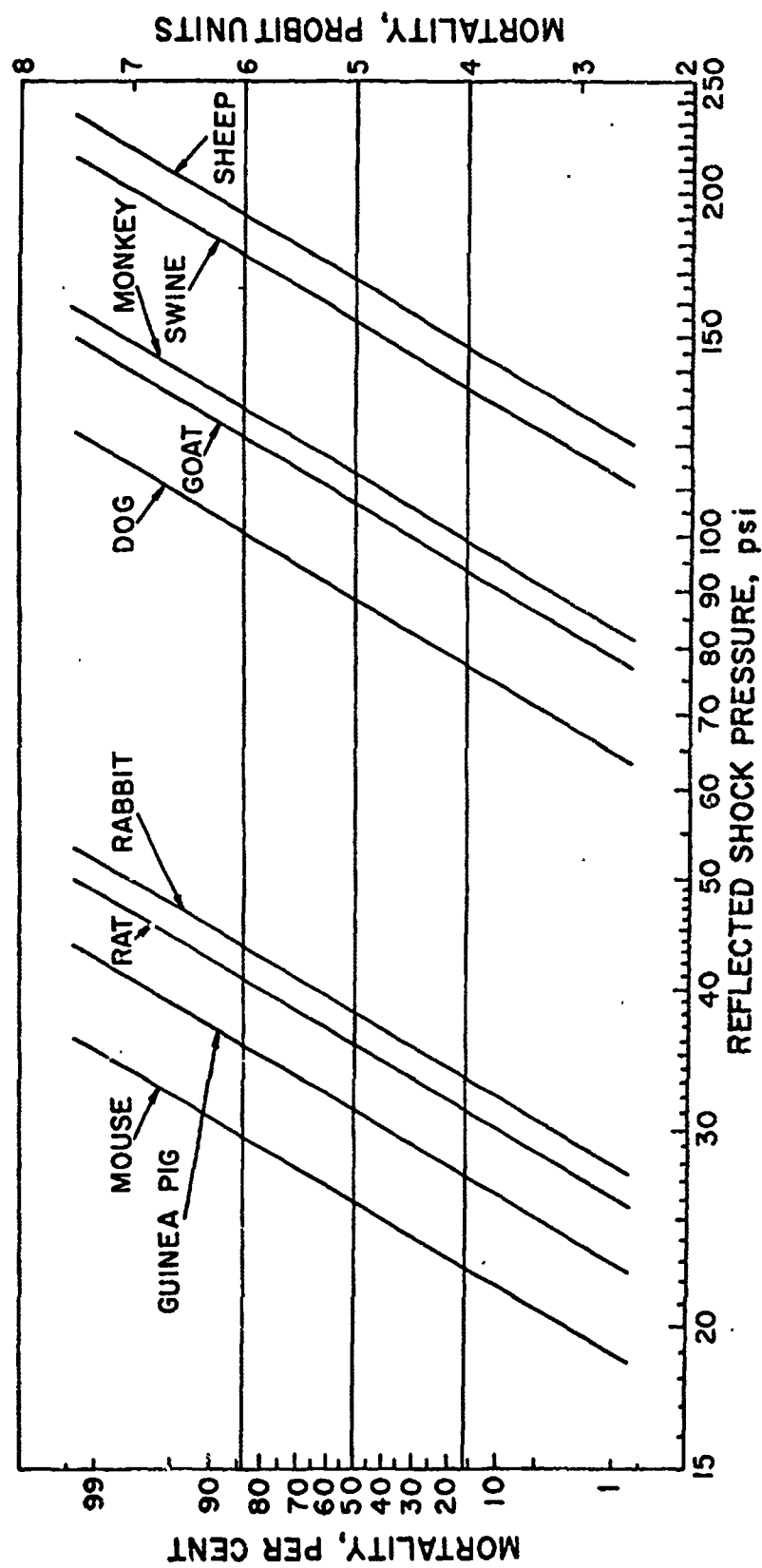
Figure 4. Mortality Curves for Animals Exposed to "Short"-Duration Reflected Pressures from High-Explosive Charges Detonated Overhead While Mounted Prone on a Concrete Pad. Probit Regression Equation: $y = a + b \log x$; Where y Is the Per-Cent Mortality in Probit Units, a and b the Intercept and Slope Constants, and x the Pressure. Data Taken from References 3, 6, and 7; All Measurements Were Made at Ambient Pressure of 12 Psia.

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TABLE 1

LD$_{50}$ AND PROBIT REGRESSION EQUATION CONSTANTS FOR
ANIMALS SUBJECTED TO "LONG"-DURATION REFLECTED PRESSURES

Species and Number	Mean Body Weight	LD$_{50}$, psi	Duration, msec	Probit Equation Constants	
				intercept, a	slope, b
Mouse 200	20.7 g	26.7 (25.5-28.0)[a]	339	-17.072	15.466[b]
Hamster 110	89.2 g	28.6 (27.1-30.0)	361	-17.513	15.466
Rat 150	200 g	30.4 (29.1-31.7)	340	-17.928	15.466
Guinea Pig 120	424 g	25.9 (24.7-27.2)	342	-16.858	15.466
Rabbit 40	3.7 kg	24.8 (22.6-27.3)	351	-16.561	15.466
Cat 48	2.5 kg	43.6 (40.3-47.3)	368	-20.361	15.466
Dog 35	15.1 kg	47.9 (44.0-52.3)	414	-20.993	15.466
Goat 30	20.5 kg	52.8 (48.0-58.1)	412	-21.637	15.466
Sheep 39	53.6 kg	54.9 (50.7-59.6)	212	-21.902	15.466
Cattle 27	180 kg	42.7 (38.7-47.0)	184	-20.211	15.466

[a] 95-per cent confidence limits.
[b] Standard error of the slope constant = ±1.368.

Note: 24-hour mortality.
Ambient pressure, 12 psia.

TABLE 2

LD50 AND PROBIT REGRESSION EQUATION CONSTANTS FOR ANIMALS SUBJECTED TO "SHORT"-DURATION REFLECTED PRESSURES

Species and Number	Mean Body Weight	LD50, psi	Duration, msec	Probit Equation Constants	
				intercept, a	slope, b
Mouse 120	22.2 g	25.9 (24.8-27.0)[a]	2.1	-19.639	17.428[b]
Rat 40	205 g	35.8 (33.4-38.3)	3.6	-22.074	17.428
Guinea Pig 82	568 g	31.4 (29.6-32.9)	3.8	-21.080	17.428
Rabbit 70	2.0 kg	38.2 (36.3-40.3)	3.6	-22.563	17.428
Monkey 12	5.7 kg	111 (97-128)	3.6	-30.659	17.428
Dog 29	16.0 kg	88.2 (80.9-96.8)	4.6	-28.908	17.428
Goat 15	22.7 kg	107 (96-119)	4.4	-30.352	17.428
Sheep 57	53.3 kg	167 (159-176)	2.9	-33.721	17.428
Swine 16	55.6 kg	154 (138-170)	2.9	-33.113	17.428

[a] 95-per cent confidence limits.
[b] Standard error of the slope constant = ±2.371

Note: 24-hour mortality.
Ambient pressure, 12 psia.

Figure 5. The Pressure-Duration Relationship and Lethality for Large and Small Animals (Mice, Hamsters, Rats, Guinea Pigs, and Rabbits). Data Taken from References 3 to 10; All Measurements Were Made at Ambient Pressure of 12 Psia.
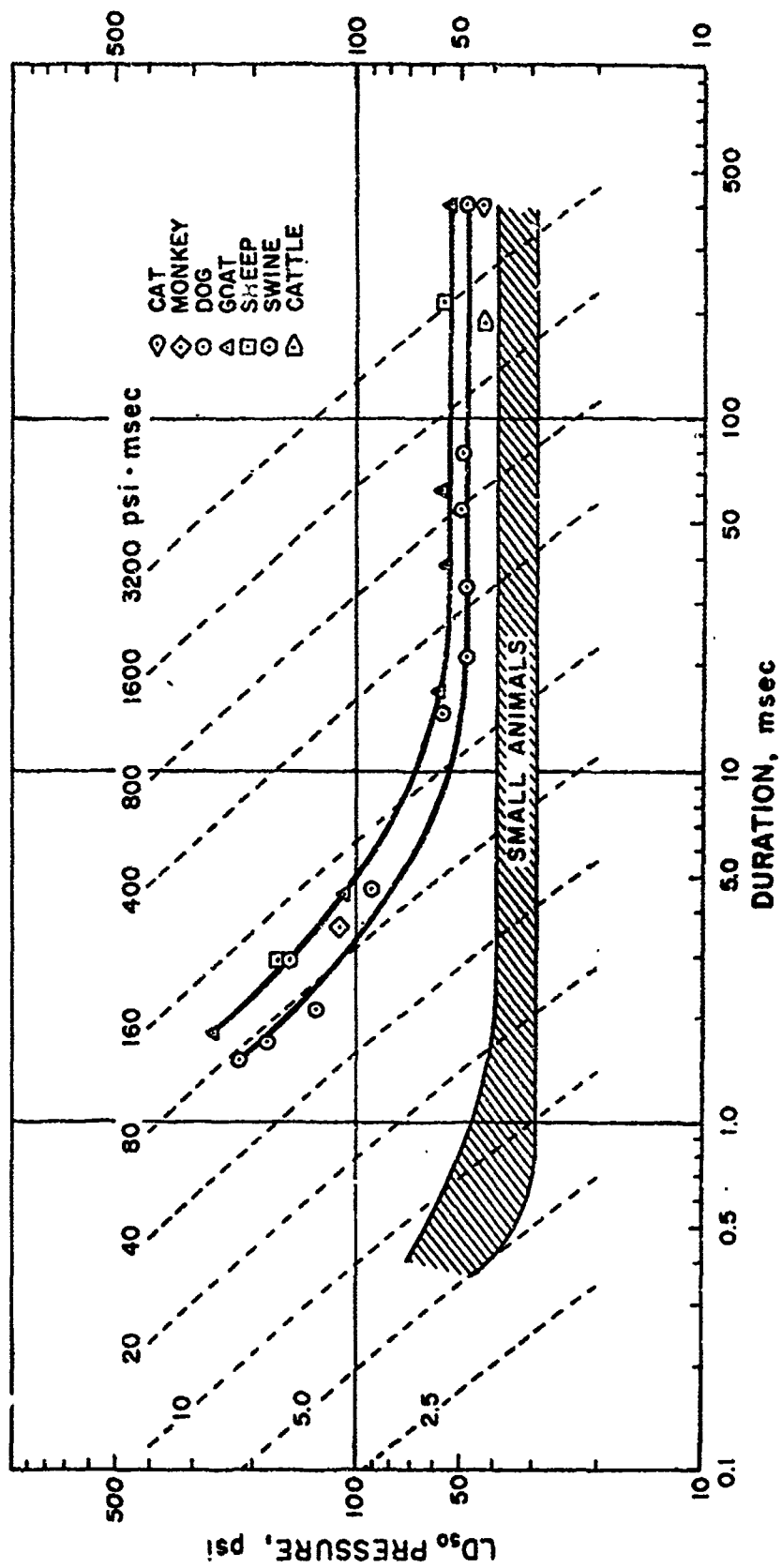
dose remains fairly constant at the "longer" durations and then climbs sharply at the "shorter" times. The curves for the larger animals (dogs and goats) bend upward around the 10- to 20-msec region, whereas, for the small species, it ranges from less than 1 msec for the mouse to around 3 msec for rabbits. At the "long"-duration end of the scale, the LD_{50} values range from near 30 to 53 psi (a factor of two) even though the animals varied in size from mice to sheep and cattle. In contrast, at the "shorter" durations, the effect depends more on species size. At the 2- to 4-msec region, the tolerance of nine species (mice to sheep) varies by a factor of about five from approximately 30 to 166 psi.

The curves appear to approach parallelism with the iso-impulse lines at the "shorter" durations. This may mean that the dose or biological response depends chiefly on the impulse. The figures are on the order of 5 to 10 psi·msec for the small animals and 80 to 120 psi·msec for larger animals. At the right end of the graph, the curves parallel the iso-pressure lines, indicating that the response depends chiefly on the peak pressure.

From the information in Figure 5, one may construct a similar curve for a mammal the body weight of man by extrapolation of interspecies correlations relating LD_{50}'s to body weight.[9] Examples of these interspecies comparisons are given in Figures 6 and 7 for "long"-duration (180 to 400 msec)[3-5] and "short"-duration (2.1 to 4.6 msec)[3,6,7] reflected pressures. From Figure 6, one calculates a 50-per cent lethal pressure for a 70-kg man of 47.6 psi and, from Figure 7, a 50-per cent lethal pressure of 147 psi. These estimates apply only to reflected pressures with exposure side-on against a reflecting surface normal to the incident shock and at an ambient pressure of 12 psia. They will be dealt with again later in this report.

EFFECTS OF ORIENTATION ON BIOLOGICAL RESPONSE TO "SHARP"-RISING PRESSURES

The results reported in this section show that, for exposure in the freestream, orientation of the biological target can significantly affect response. Figure 8[3] compares the 50-per cent lethal conditions for guinea pigs in different positions in the freestream of an open 12-in. diameter shock tube (Figure 2B) with those against the closed end of the same tube (Figure 2A). In the former situation, the duration was beyond 15 msec and, in the latter, several times that. Both of these may be considered to be very "long" for an animal of that size. The bar graph shows that, in terms of side-on incident pressures, 17 to 18 psi accounted for 50-per cent lethality for those suspended vertically or prone-broadside; whereas incident pressures of 25 to 26 psi were required for the same effect with those head-on or tail-on. For animals against a reflecting surface, the incident shock pressure was the lowest (10 psi). There was better agreement between LD_{50} pressures for the different conditions when the dynamic pressure was added to the side-on pressure as the maximal effective dose the upright and prone-side-on animals received. A comparable figure was the side-on pressure for the end-on animals. The maximal reflected pressure was the significant parameter or maximal effective dose for those tested against the endplate of the shock tube. Whether the very transient reflected shock from the animal itself was involved in contributing to the effective dose cannot be stated at this time.
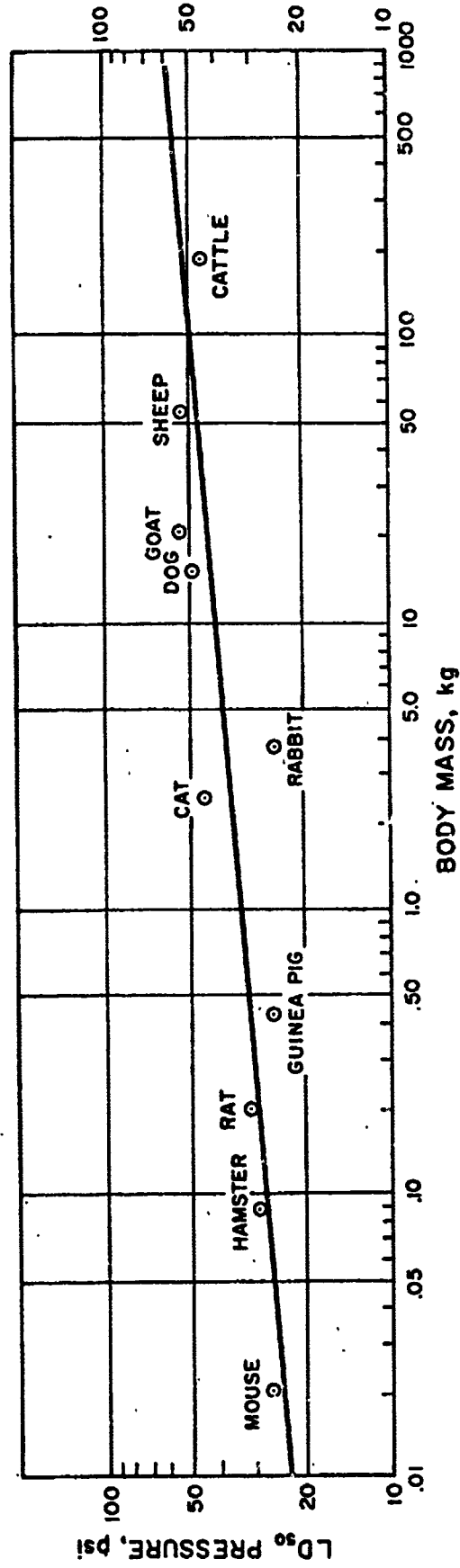
Figure 6. Relationship of LD50 Pressure to Body Weight for Mammals Exposed to "Long"-Duration Reflected Pressures at an Ambient Pressure of 12 Psia. Regression Equation: Log LD50 = 1.5275 + 0.0812 log m. Data Taken from References 3 to 5.
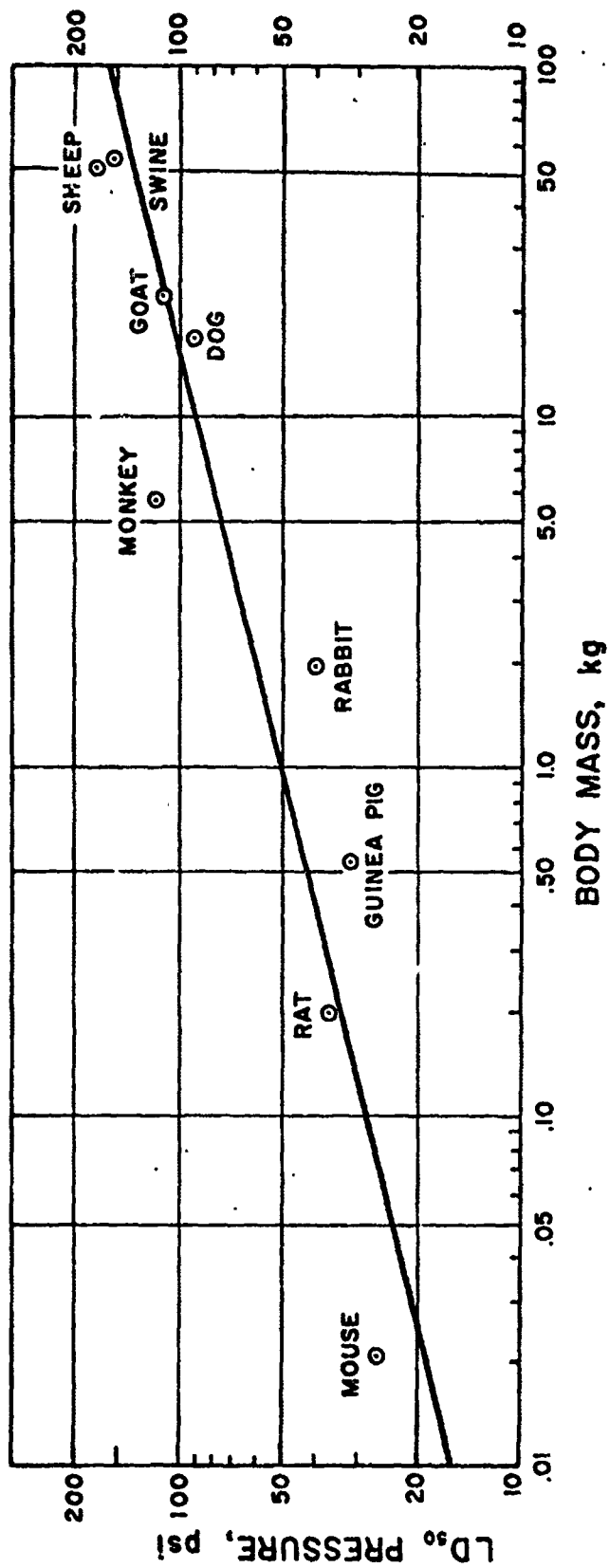
Figure 7. Relationship of LD_{50} Pressure to Body Weight for Mammals Exposed to "Short"-Duration Reflected Pressures at an Ambient Pressure of 12 Psia. Regression Equation: $Log\ LD_{50} = 1.7055 + 0.2502\ log\ m$. Data Taken from References 3, 6, and 7.

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LEGEND

REFLECTED PRESSURE- P_f

DYNAMIC PRESSURE- P_Q

INCIDENT PRESSURE- P_s

95% C.L.

Figure 8. LD$_{50}$ Conditions for Guinea Pigs in Various Orientations. Reproduced from Reference 3; All Measurements Were Made at Ambient Pressure of 12 Psia.

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Studies are under way to extend these findings to a large species using "short"-duration air blasts.[7] Sheep, at different orientations and at several ranges, are exposed in the open to blasts from 64-lb charges at and above 6-ft heights-of-burst. Based on the response of sheep to "short"-duration reflected pressures on the surface already mentioned in Table 2 (LD$_{50}$ and 95-per cent confidence limits of 167 psi and 159 to 176 psi, respectively), one would expect 50-per cent lethality for vertically suspended and prone-broadside animals at a distance where the side-on plus dynamic pressure is within the figures shown, and at distances where the side-on presqures are of that order for end-on animals.

Some of these results which appear in Table 3 show that the upright and prone-broadside sheep experience 50-per cent lethality at 18 ft where side-on plus dynamic pressures recorded were on the order of 177 psi. The head-on animals all surviv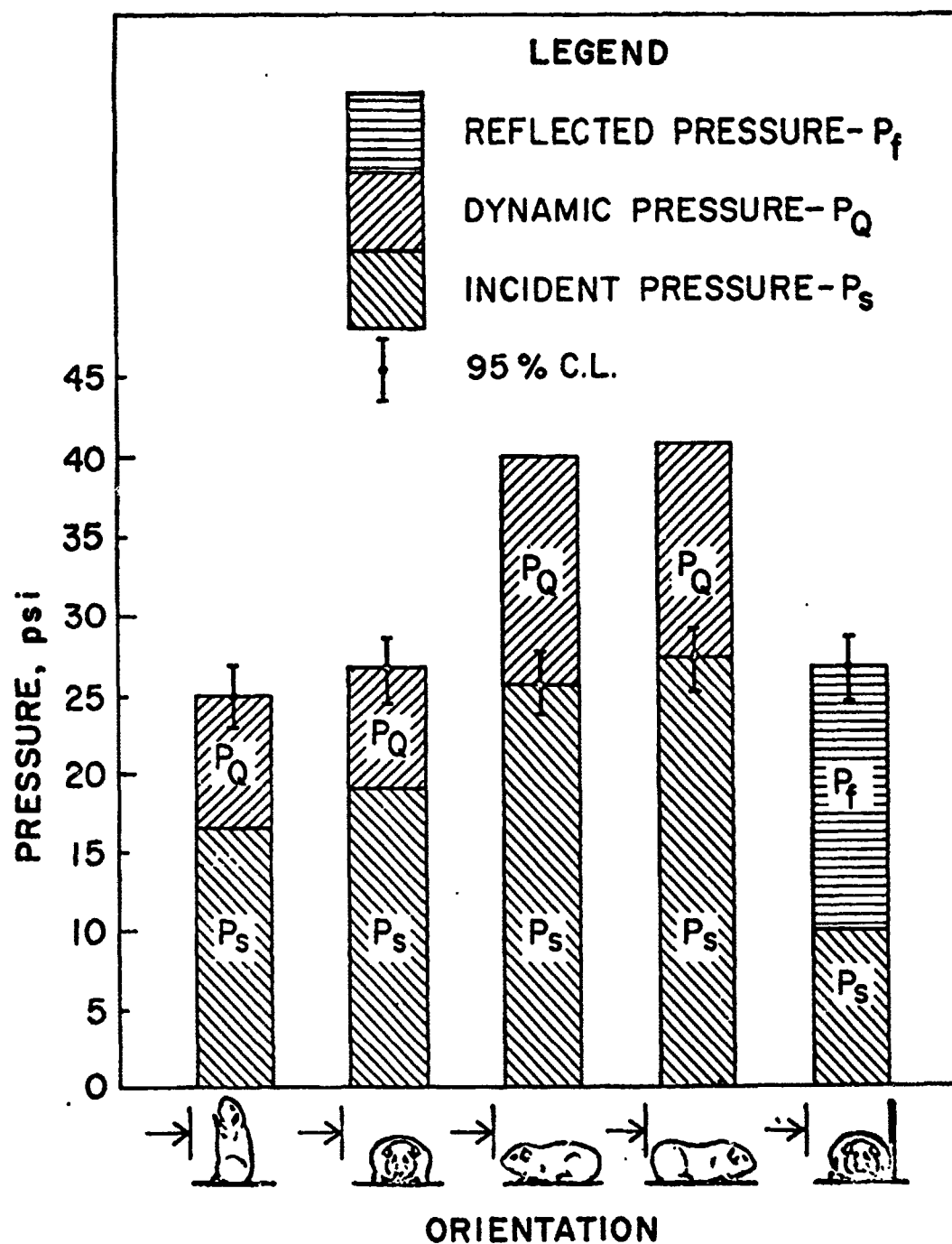ed at that range where the incident side-on pressure was 83 psi. The latter would have to be placed at closer ranges to sustain 50-per cent mortality.

BIOLOGICAL RESPONSE TO BLAST WAVES
THAT RISE IN TWO STEPS

It has been found that animals can withstand higher reflected pressures if they are beyond a certain distance from the reflecting surface rather than against it. Those located short distances upstream from a reflecting surface are first struck with the incident shock and then, a very short time later, by the reflected shock from the opposite direction. The time between shocks is related to the distance from the surface, and to some extent by the shock strength. Figure 9 gives the mortality for five species tested side-on at various distances from the endplates closing the 24- and 40-in. diameter shock tubes.[9,10] They were exposed to "square" waveforms of "long" duration similar to those already shown in Figure 2, records a and b. The incident shock pressure was 18 psi and reflected to 52 psi. The reflected shock pressure does not decay in the shock tube at these distances as it does for "short"-duration waves in the open. These pressures produced 100-per cent lethality for mice, rats, guinea pigs, and rabbits and 50-per cent mortality for dogs when all were against the endplate. As the subjects were moved away from the reflecting surface (endplate), there was, for each species, a certain distance where the per-cent lethality dropped. These distances were directly related to species size or, more specifically, to their body width. Apparently, at a certain distance, a particular species would experience the incident and reflected shocks as two separate events, which were less damaging than at shorter distances where they were one. The times between shocks required for greater resistance were on the order of 0.04 msec for the mouse and 0.38 to 0.71 msec for the dog.

The surprising thing was that the reflected shock in the second step, given by itself, would be more lethal than the two combined. It is almost as if the first step "protects" the target from the second. It may be that the first step, if not in itself a lethal dose, may protect the animal from the second shock by effectively providing a new and higher ambient pressure externally as well as intrathoracically, thereby making the second shock less effective. Shock-tube studies have made it clear that as the

TABLE 3

EFFECT OF ORIENTATION ON THE RESPONSE OF SHEEP
TO "SHORT"-DURATION AIR BLASTS

| Orientation | Pressure, psi | | Duration, msec | Lethality at 18 ft* |
	Side-On	Side-On Plus Dynamic		
Prone-Head-On	83	177	3.6	0/4 0%
Prone-Side-On	83	177	3.6	3/6 50%
Suspended Vertically-Facing	83	177	3.6	4/8 50%

* Ground range from 64-lb TNT charges detonated at a 6-ft height-of-burst.

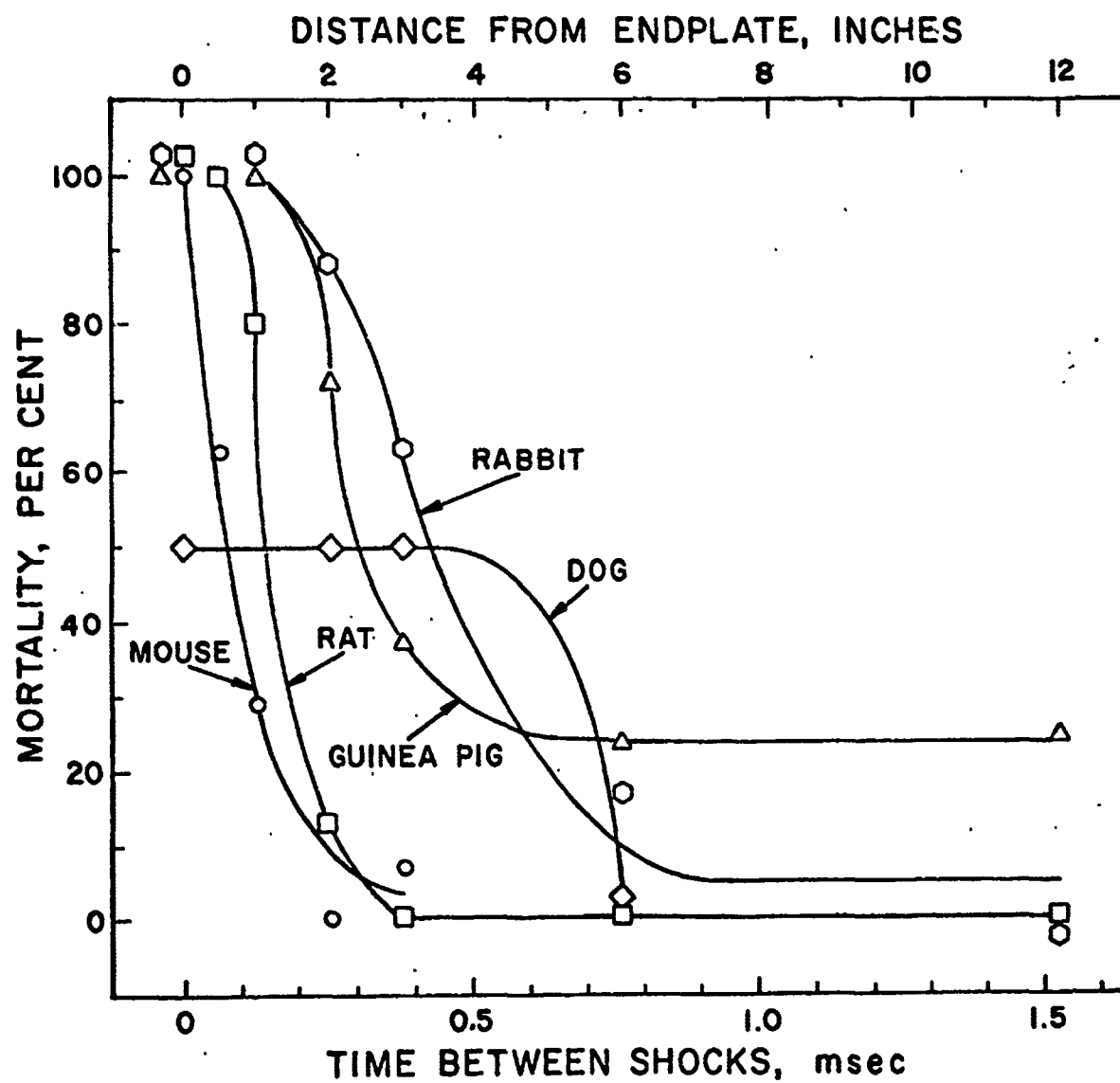Note: Ambient pressure, 12 psia.
  Reference 7.

Figure 4. Tolerance of Animals to Reflected Pressures as a Function of Time Between Incident and Reflected Shocks. Mean Incident and Reflected Pressures Approximately 18 and 52 Psi, Respectively. All Measurements Were Made at an Ambient Pressure of 12 Psia. Data Taken from References 9 and 10.

barometric pressure at the time of exposure is increased, animals' resistance to blast goes up proportionately. [11, 12]

Investigations with blast waves that rose in two steps have been reported for peaked waves from high-explosive charges fired in the open. [13] In terms of peak reflected pressure, rats' tolerance was the same with the reflecting plate at 0 and 4 cm from their necks with time-steps of 0 and 0.15 msec, but tolerance rose when the plate was 10 cm with a time-step of 0.3 msec.

Thus, in terms of LD_{50} reflected pressures, there appears to be a 50- to 100-per cent increase in resistance when sufficient time (distance) separates the two shocks.

BIOLOGICAL RESPONSE TO "SLOW"-RISING BLAST PRESSURES

In general, biological systems are remarkably tolerant to pressure pulses that rise in a "smooth" manner without the presence of shock fronts. Such waveforms have been recorded in personnel shelters subjected to nuclear blast that filled through small openings. In our laboratory experiments, dogs have survived maximal pressures of 74 to 167 psi that rose to peak in 30, 60, 90, and 155 msec (Table 4). [4, 15] The leading portions of the pressure waveforms are shown in Figure 10 and were of 10-, 10-, 20-, and 5-sec durations for records a, b, c, and d, respectively. The blast injuries consisted of eardrum rupture, marked sinus hemorrhage, and, in some cases, isolated lung hemorrhages of a trivial nature. The latter were along the margin of the costophrenic portions of the lungs. Small animals showed a similar resistance to these pressure patterns. Guinea pigs sustained pressures of 50 to 80 psi having rise-times of 20 msec and beyond and from 0.8 to 25 sec in duration. Mice survived pressures up to 122 psi with rise-times on the order of 20 to 30 msec.

That animals can resist very high, "smooth"-rising pressures was well illustrated by the work of Wünsche. [16] Rats survived exposure in a pressure vessel to 28 atm with a rise-time of 0.5 to 0.6 sec. The hold-times were 10, 20, 30, and 40 sec and the decay or decompression times were 4.35, 1.20, and 0.2 min. At higher pressures of 33 to 46 atm, mortality did occur, but it was related to hold-time and time of decompression and not to the initial loading phase.

SELECTED BLAST INJURIES

Lung Injury

Lung damage is responsible for the classic external sign of blast damage: exudation of blood or bloody froth from the mouth and nostrils. One must hasten to add that, under some circumstances, sinus hemorrhage may contribute to this. Although the auditory mechanism is probably the system most sensitive to the air blast, the lungs may be considered the critical target organ. Lung damage initiates the sequence of physiological changes in the body that may lead to the death of the animal. Especially important is the origin of air bubbles, apparently from disrupted alveoli of the lungs. These appear in the vascular system where

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TABLE 4

EFFECTS OF "SLOW"-RISING PRESSURES ON DOGS

Group	Maximum Pressure, psi	Time to Maximum Pressure, msec	Duration of Pressure, sec	Pathology Eardrum Rupture	Pathology Sinus Hemorrhage	Pathology Pulmonary Hemorrhage
I	74-130	27-30	10	100%	100%	50%
II	130-170	60-64	10	100%	100%	100%
III	110-156	84-90	20	100%	100%	50%
IV	116-167	152-158	5	100%	100%	0%

Note: There were four animals per group.
Pulmonary hemorrhages were of a trivial nature.
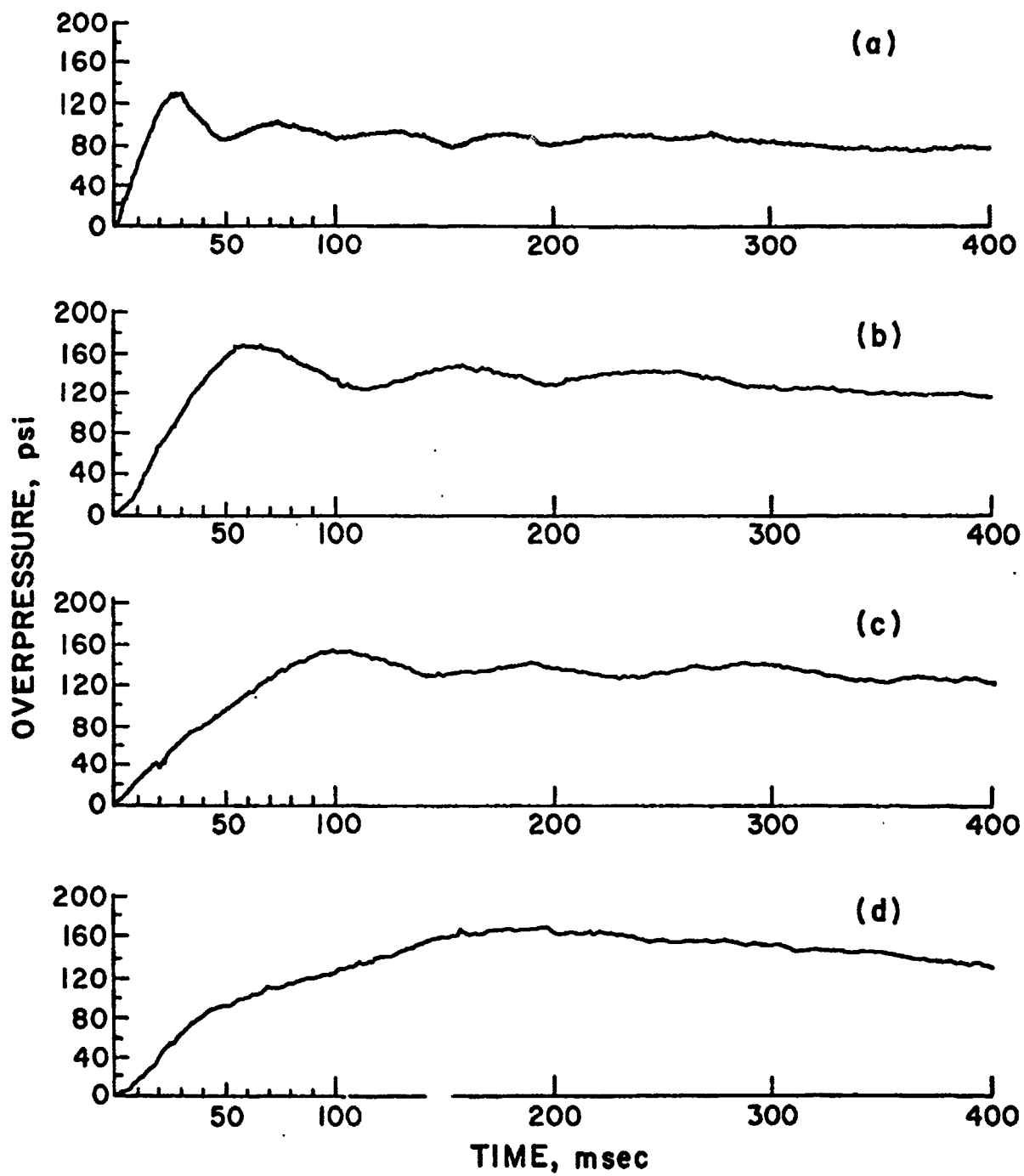Ambient pressure, 12 psia.
References 14, 15.

Figure 10. "Slow"-Rising Pressure-Time Patterns with Various Rates of
Rise. Recordings Made at Ambient Pressure of 12 Psia. Data
Taken from Reference 14.

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their quick transport to various organs, including the heart and brain, leads to a rapid death. Air bubbles are also the probable cause of symptoms of central nervous system disorders observed in animals subjected to intense air blast, and of infarcts found in the hearts and kidneys of blasted survivors.[4,5] It was important, therefore, to learn the relationship between lung injury and intensity of air blast.

The degree of lung injury inflicted by graded doses of air blast in dogs at and below the lethal level is summarized in Figure 11.[3, 17, 18] It gives the lung weight and degree of pulmonary hemorrhage in relation to the magnitude of "long"-duration reflected pressure in a shock tube. Any increase in the lung weight of a blasted animal above control values gives an indication of the amount of blood and/or edematous fluid in that organ. As seen in Figure 11, petechial hemorrhages first appeared in dog lungs at 12 to 16 psi. Small, isolated hemorrhages were produced at 20 to 30 psi. It was not until pressures reached the lethal range that more serious confluent hemorrhages occurred and lung weights increased importantly above control values. The LD_1 and 95-per cent confidence limits calculated for dogs subjected to reflected pressures of 20- to 40-msec duration were 36.3 psi and 30.9 to 39.1 psi, respectively. At LD_{50} levels, 48.2 psi (46.6 to 50.3), the lung weight can be as much as two to four times the normal. It appears that the threshold for petechial lung hemorrhage in dogs amounts to approximately one-fourth of the LD_{50} dose and more serious injury occurs at about three-fourths of the LD_{50}.

Microscopic examination of the lung tissues revealed emphysematous changes (enlargement and disruption of the alveolar septa) in and adjacent to the hemorrhagic areas. In the lungs of animals given 20 psi and above, perivascular and peribronchial clefting and stripping of the bronchial epithelium were common findings.

For animals in the two groups exposed to 15 psi and less that exhibited neither petechia nor lung hemorrhage, the blast had no detectable effect on their heart and respiratory rates. Neither could any changes be detected in the electrocardiograms of these animals. However, the respiratory rates of dogs having small, isolated hemorrhages usually increased at 20 to 40 min after exposure. Usually, confluent pulmonary hemorrhages produced an immediate increase in the respiratory rate and the animals' breathing was rapid and shallow. Significant slowing of the heart rate was noted only in animals that received lethal blast doses.

Once the relationship between the degree of lung injury and the pressure dose was worked out in some detail for one of the larger species, it was possible to determine the threshold level in other large species for other conditions of exposure using fewer animals.

For "long"-duration pressures, the threshold for petechial hemorrhage in the lungs of goats was found to be near 10 psi (side-on pressure) having a duration of 230 msec. The animals were exposed in the open, right-side-on at a ground range of 960 ft from a 500-ton TNT charge in the form of a hemisphere at a barometric pressure of 13.6 psia.[17] Similar values for sheep against the endplate of a shock tube, with an ambient pressure of 12 psia, were found to be between 16 and 18 psi for reflected pressures near 100- and 120-msec durations.[7]
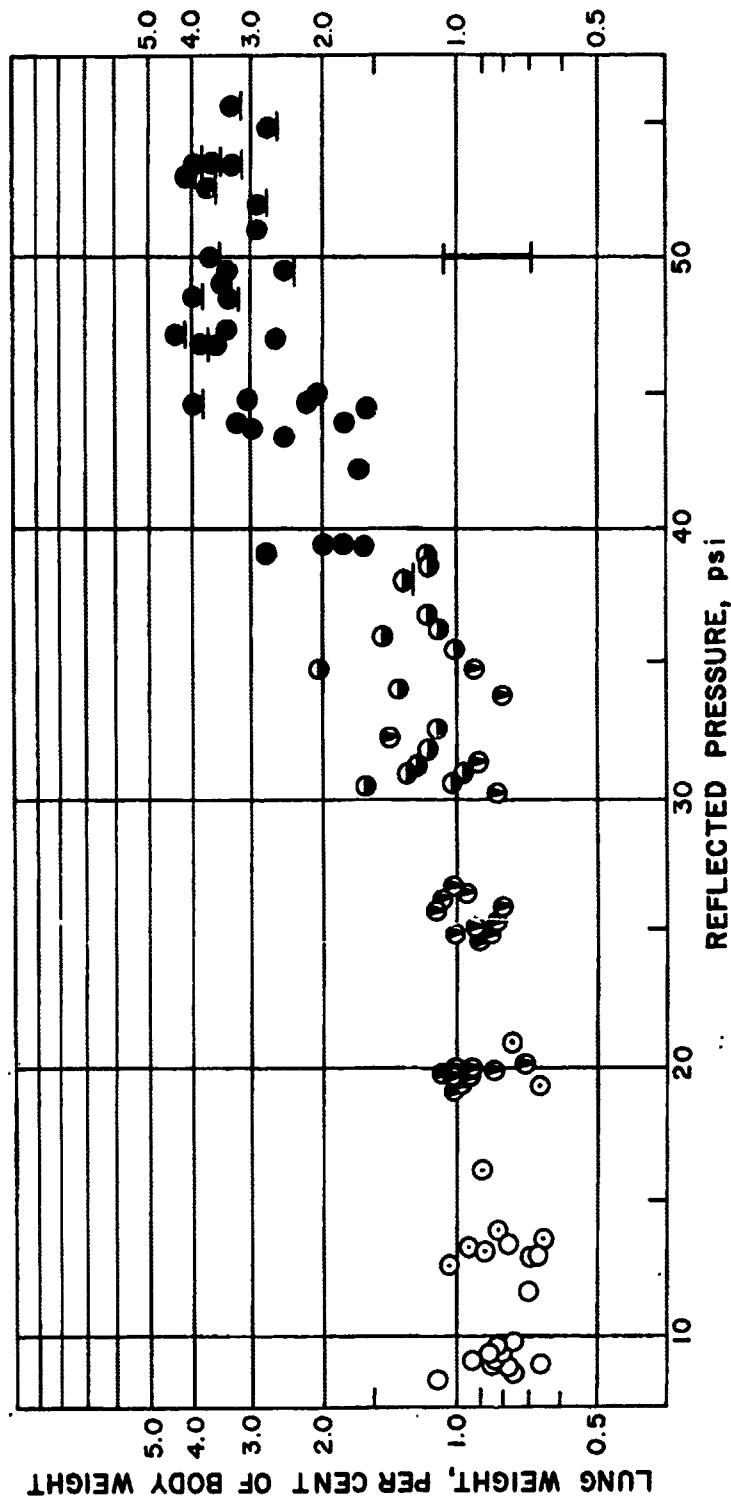
Figure 11. Relation Between Lung Injury in Dogs and Reflected Pressures of "Long" Duration at an Ambient Pressure of 12 Psia. Data Taken from References 3, 17, and 18.

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Figure 12 presents the lung weight and extent of pulmonary hemor-
rhage for sheep exposed to "short"-duration reflected pressures of vari-
ous levels at an ambient of 12 psia. [7] From this the threshold for lung
damage in sheep can be seen to be around 30 to 35 psi (duration of 5.7
msec, 64-lb charge at 32-ft burst height). The animals were prone on a
concrete pad with charges detonated overhead as already described. The
threshold, in this case, was slightly less than one-fourth of the LD_{50} dose
of 166 psi with 64-lb charges because of the "longer" duration encountered
as the distance from the charge was increased in going from near LD_{50}
heights (17 ft) with durations of 3 msec to 32-ft heights with 5.7-msec
durations. It seems safe to generalize on the matter and use one-fourth
of the dose as the beginning of lung injury and three-fourths of the LD_{50}
(about the threshold for lethality) as the beginning of severe lung injury.

Ear Injury

A subsequent paper at this conference by Dr. F. G. Hirsch will re-
view the information on ear injury.* Even though no systematic studies on
ear injury have been undertaken at this laboratory to date, a few remarks
should be made in passing. First, there is a remarkable variation en-
countered in eardrum responses. For instance, in Operation Snow Ball
where a 500-ton TNT charge was detonated on the surface, the eardrum
rupture in goats exposed side-on in the open ranged between 55 per cent
at 10 psi (965-ft range) and 75 per cent at 60 psi (430-ft range). At seven
ranges between the above, the percentage of eardrums ruptured seesawed
from 67 to 100 per cent. [17]

Second, the data in Table 5, from the sheep threshold lung studies,
suggest there may be a duration effect. At "long" durations, 38-per cent
rupture was recorded at 21.4 psi; whereas there were no eardrums rup-
tured at 32.4 psi when the durations were "short." In these particular
experiments, the pinnae of the sheep were taped to the tops of their heads
so they would not act as flapper valves.

Third, although one would suspect that the orientation of the head
would have a marked effect on eardrum rupture, a cursory survey of the
data failed to provide adequate numbers to substantiate this. That is, for
animals tested side-on in the freestream, the side of the head facing the
blast (the outer canal) should be loaded with higher pressures than on the
opposite side.

Fourth, in very general terms, the severity of ear damage grows
with the intensity of the blast. The degree of ear injury ranges from ear-
drums intact with slight hemorrhages, eardrums partly gone, eardrums
completely missing, to eardrums absent and ossicles (particularly the
malleus) either disrupted or fractured.

ESTIMATION OF MAN'S RESPONSE TO "SHORT"-DURATION AIR BLASTS

Table 6 summarizes the maximal effective pressures estimated to
produce various levels of eardrum rupture, lung injury. and lethality in

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*To be published as a Technical Progress Report No. DASA 1858.
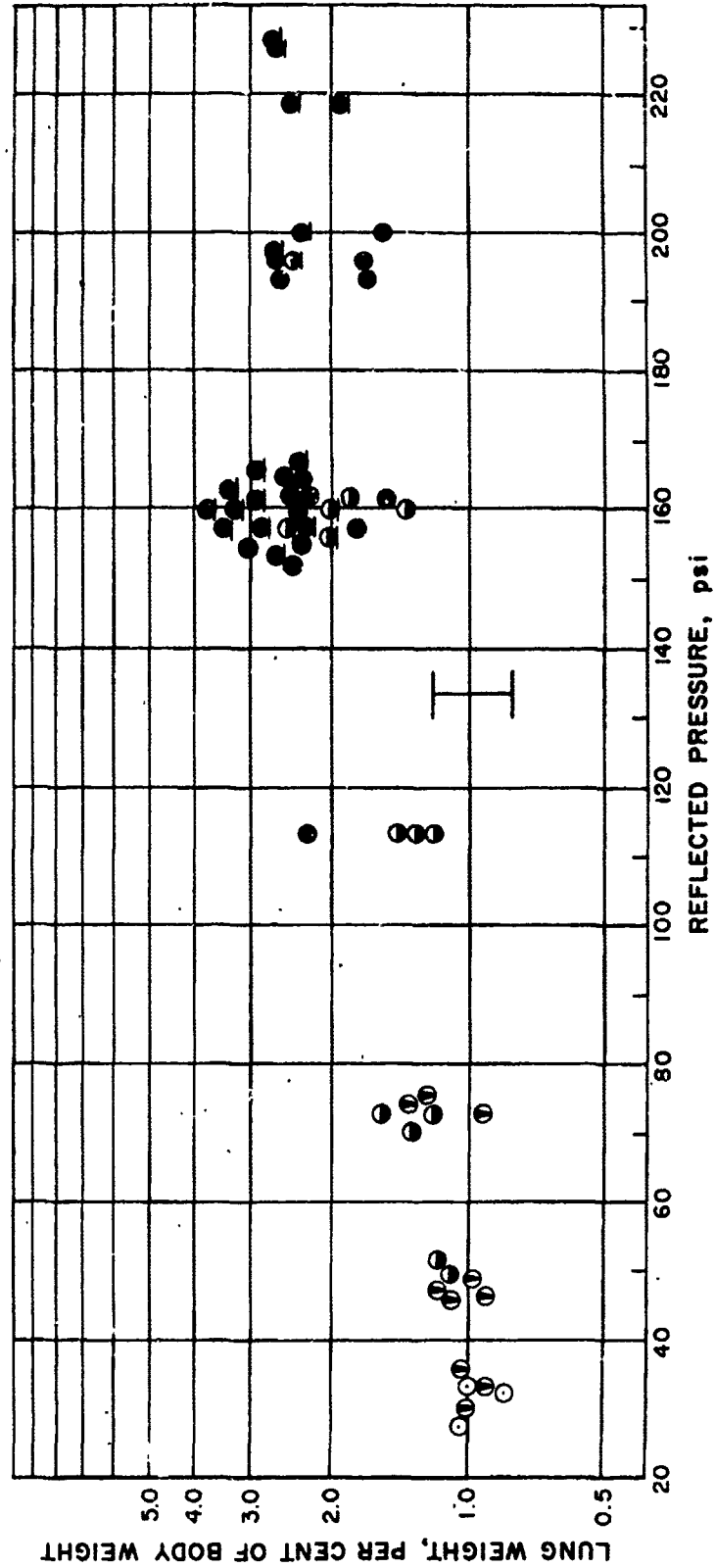
Figure 12. Relation Between Lung Injury in Sheep and Reflected Pressures of "Short" Duration at Ambient Pressures of 12 Psia. Data Taken from Reference 7.

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TABLE 5

COMPARISON OF EARDRUM RUPTURE IN SHEEP FROM
SUBLETHAL PRESSURES OF "LONG" AND "SHORT" DURATION

Reflected Pressure, psi	Duration, msec	Eardrums Ruptured			Per Cent of Eardrums Ruptured
		Right Only	Left Only	Both	
"Long" Duration:					
10.3	98	0/4*	0/5	0/5	0
17.7	124	1/5	0/5	0/5	10
21.4	121	1/4	0/4	1/4	38
"Short" Duration:					
32.4	5.7	0/6	0/5*	0/5*	0
47.9	5.2	1/6	0/6	3/6	58
73.9	4.8	1/6	0/6	3/6	58

* One animal not assessed.

Note: Ambient pressure, 12 psia.
      Reference 7.

TABLE 6

TENTATIVE CRITERIA FOR PRIMARY-BLAST EFFECTS
IN MAN APPLICABLE TO "FAST"-RISING AIR BLASTS
OF "SHORT" DURATION (3 MSEC)

Crital Organ or Event	Maximal Effective Pressure, psi*
Eardrum Rupture:	
Threshold	5
50 Per Cent	15
Lung Damage:	
Threshold	30-40
Severe	80 and above
Lethality:	
Threshold	100-120
50 Per Cent	130-180
Near 100 Per Cent	200-250

* Effective pressure can be the incident, reflected, or incident plus dynamic, depending on one's geometry of exposure and the location of the explosion (see text for an explanation).

Note: Ambient pressure, 12 psia.

man. It should be emphasized that the range of pressure levels indicated, for a given effect, are a first approximation and no doubt will be revised as work in this area progresses. Furthermore, since the duration has such a marked effect on the pressures required for a given level of response, those figures given can apply only to air blasts of near 3-msec duration. Except for the eardrum estimates, they are based on the results from experimental animals.

The pressures required for 50-per cent lethality for man of 130 and 180 psi (ambient pressure, 12 psia), estimated from Figure 7, are lower than those previously predicted of 390 to 470 psi (sea level)[19] and 431 psi (ambient pressure of 12 psia).[9] The latter were based on interspecies studies involving only five and six animal species of which two were large. The 130- to 180-psi value given in Table 6 is in closer agreement with a 100 psi at 6.6-msec duration lethal limit based on an analysis of an actual human exposure and dog experiments at sea level[1] and the 188 psi at 3-msec duration scaled recently from dog and goat data.[18,20] A detailed comparison of these values will be dealt with in a subsequent paper at this conference by Mr. Bowen.*

The threshold for lethality (100 to 120 psi) was obtained by assuming man's dose-response curve would parallel those of the experimental animals reported here. The values for lung damage threshold, between 30 to 40 and for severe, 80 psi or above, were based on the threshold studies involving sheep, dogs, and goats described earlier in this report. The pressures of 5 and 15 psi required for threshold eardrum rupture and 50-per cent, respectively, were from a subsequent paper in this conference by Dr. F. G. Hirsch.** There are insufficient data to refine them at the present time.

The maximal effective pressure may be the incident pressure, the incident plus dynamic, or the reflected pressure, depending on one's geometry of exposure and location of the charge. If the biological target is against a reflecting surface that is normal to the incident shock wave or if the individual is prone and the charge detonated overhead, the reflected pressure becomes the maximal effective pressure. The side-on plus dynamic pressure becomes the effective pressure for individuals standing or prone-side-on to the charge when it is detonated at or near the surface. When the biological targets are oriented end-on to the explosive source, the side-on incident shock pressure appears to be the maximal effective pressure.

Personnel would be subjected to pressures that rise in two steps if they were standing with the charge detonated overhead or if they were standing a few feet from a reflecting surface that was normal with respect to the incident shock. In the former instance, the side-on pressure in the first step would probably be the effective dose; in the latter, the side-on plus dynamic pressure in the first step. The reflected wave would have decayed to noninjurious levels by the time it returned to the thoracic region. It could, however, add to the duration and impulse of the wave, but since it is at the aft end of the pulse, it might not be of significance. Moreover, the time-step between the incident and reflected shocks would

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* To be published as a Technical Progress Report No. DASA 1857.
** To be published as a Technical Progress Report No. DASA 1858.

be several milliseconds, which, even if the wave were of "long" duration, would not make the reflected pressure dangerous. The exact distance from a reflecting surface where the effective pressure changes from the reflected to incident or incident plus dynamic cannot be stated for man at this time. Nor can anything be said about exposure on a reflecting surface hit at various angles of incidence with the shock wave.

As far as lung injury is concerned, the foregoing remarks on maximal effective pressure should apply. That is, the threshold would be 30 to 40 psi reflected pressure for personnel against a reflector. For those in the open standing or prone-side-on, it would be 30 to 40 psi, of which 20 to 25 psi would be the incident pressure plus 10 to 15 psi dynamic pressure. Thirty to forty psi incident pressure would be required for personnel prone-end-on.

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